Circulating Fluidized Bed Boiler Technology

A competitive option for CO₂ capture through oxyfuel combustion?

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Nicklas Simonsson, Vattenfall Research & Development AB
Timo Eriksson, Foster Wheeler Energia Oy
Minish Shah, Praxair Inc.
Outline

1. Air CFB boiler technology
   - Development trends
   - Current state of the art
   - Main principles and benefits

2. Hamburg CHP oxyfuel CFB conceptual design study
   - Objective
   - Design basis
   - ASU and CO$_2$ processing unit
   - Boiler design
   - Techno-economical results

3. Summary and conclusions
Air CFB Technology – Development trends

- Traditionally CFB boilers characterised by
  - Small unit sizes
  - Low/moderate steam data
  - Mainly used in applications with difficult to use fuels and biomass

- Significant scale up of unit size and increase of steam data during last decade

- Today CFB technology must be considered a competitive option also for large-scale utility applications

Source: Foster Wheeler
Air CFB Technology – Current state of the art

Foster Wheeler Lagisza CFB unit

- Worlds largest and first supercritical CFB boiler
- Handed over to customer in Poland in June 2009
- 460 MW_e gross
- 275bar/560°C/580°C
- 290°C feed water temperature
- >43% net efficiency

The Foster Wheeler Lagisza CFB boiler – from conceptual design to existing plant

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Air CFB Technology – Principles and benefits

- Combustion of fuel in a high bed inventory consisting of a mixture of fuel, ashes and sorbent (limestone). Bed suspended or fluidised through air entering the bottom of furnace

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>BENEFIT</th>
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| Low furnace temperatures | Low NO\textsubscript{x}  
                         | Low SO\textsubscript{2}                              |
| Hot circulating solids | Fuel flexibility  
                         | Handles low grade fuels  
                         | Simple feed systems |
| Long solid residence time | Good fuel burnout  
                        | Good sorbent utilization |

Source: Foster Wheeler
Hamburg OxyCFB CHP conceptual design study

Objective:
• To evaluate the competitiveness and possibilities of CFB technology in oxyfuel applications

Study performed in close cooperation with:
• Foster Wheeler (boiler design)
• Praxair (ASU and CO₂ compression)

Design basis:
• Hamburg site conditions
• Bituminous coal (LHV 25.1 MJ/kg)
• 500 MWₑ gross
• 0-400 MWₑ_DH (output and temperature levels varying during the year)
• Both air and oxyfuel cases investigated
• CO₂ capture rate >90%

The Tiefstack CHP plant – one of several units delivering district heating to the city of Hamburg. The Hamburg district heating network consist of over 770 km pipelines.
Hamburg OxyCFB CHP conceptual design study

Included activities:

- Conceptual boiler design, performance, cost and layouts for air and oxyfuel
- ASU and CPU design, performance, cost and layouts
- Flue gas cleaning options
- ASU O₂ purity sensitivity and optimisation study
- Detailed overall plant H&MB calculations
- Overall plant heat integration optimisation
- Plant Layout
- Economical evaluations
- Risk assessment

Flow sheet from the H&MB calculations (above) and the resulting OxyCFB plant layout.
ASU and CO₂ compression and purification unit designs

• Unit designs based on Praxair’s state of the art

• Air separation unit
  – Dual trains with total capacity 7088 TPD O₂ (contained) @ 1.3 bar and 172°C
  – Optimisation study – 97%-vol O₂ purity selected
  – Low temperature heat recovery to DH network

• CO₂ processing unit
  – Single train (with two parallel compression units) with total capacity of 7860 TPD CO₂ contained (inlet flue gas CO₂ concentration ~85%-vol)
  – CO₂ capture rate 93.3%
  – CO₂ product quality 96.1%-vol. @ 110 bar and 30°C
  – Low temperature heat recovery to DH network and heat integration for vent gas expansion
  – No provisions for SOₓ and NOₓ removal – although pursued by Praxair for future developments
Air- and oxyfuel CFB boiler design

- Existing 460 MW_{e,gross} Lagisza boiler design used as starting point
  - Low mass flux BENSON once-through technology with vertical furnace tubes
  - Sliding pressure operation

- Steam data – representative for given time frame
  - Steam data: 600°C/620°C /290 bar
  - Feed water temp: 300°C

- Assumptions OxyCFB design (compared to AirCFB)
  - HP steam flow kept constant
  - Furnace velocities similar as in air firing
  - Same flue gas excess O₂ content (3.6%-vol, dry)
  - Oxidant O₂ so that adiabatic combustion temperature does not exceed that of air firing
  - Same Ca/S ratio
  - Air ingress 1% of flue gas flow
OxyCFB process flow diagram – flue gas side
## Overall plant technical & economical key data

<table>
<thead>
<tr>
<th></th>
<th>AirCFB Condens</th>
<th>AirCFB DH</th>
<th>OxyCFB Condens</th>
<th>OxyCFB DH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel input</strong> [MW]</td>
<td>1052</td>
<td>1052</td>
<td>1047</td>
<td>1047</td>
</tr>
<tr>
<td><strong>Gross Power</strong> [MW\textsubscript{e}]</td>
<td>506</td>
<td>469</td>
<td>516</td>
<td>482</td>
</tr>
<tr>
<td><strong>Net Power</strong> [MW\textsubscript{e}]</td>
<td>472</td>
<td>435</td>
<td>381</td>
<td>347</td>
</tr>
<tr>
<td><strong>District heating</strong> [MW\textsubscript{th}]</td>
<td>-</td>
<td>269</td>
<td>-</td>
<td>269</td>
</tr>
<tr>
<td><strong>Net efficiency</strong> [%]</td>
<td>44.9</td>
<td>41.4</td>
<td>36.4</td>
<td>33.2</td>
</tr>
<tr>
<td><strong>Total efficiency</strong> [%]</td>
<td>-</td>
<td>67.0</td>
<td>-</td>
<td>59.9</td>
</tr>
<tr>
<td><strong>Specific invest.</strong> [€/kW\textsubscript{e} net]</td>
<td>1621</td>
<td>1703</td>
<td>2952</td>
<td>3096</td>
</tr>
<tr>
<td><strong>COE</strong> [€/MWh\textsubscript{e}]</td>
<td>39.8</td>
<td>28.1</td>
<td>65.6</td>
<td>52.7</td>
</tr>
<tr>
<td><strong>CO\textsubscript{2} avoid. cost</strong> [€/ton CO\textsubscript{2}]</td>
<td>-</td>
<td>-</td>
<td>37.9</td>
<td>33.4</td>
</tr>
</tbody>
</table>

*Yearly average values due to varying DH output and temperature levels.

- DH can significantly improve plant economics
- Slightly higher COE and CO\textsubscript{2} avoid. cost compared to PF cases on equal basis. However:
  - Uncertainties in investment costs between studies
  - Not considered that CFB cases potentially could utilise lower quality fuels more cost effective

*CFB could very well be competitive – both with and without CO\textsubscript{2} capture!*
Hamburg OxyCFB study – Summary

- Established air CFB advantages also valid for OxyCFB
  - Fuel flexibility (Hard coal, Lignite, Biomass)
  - Possibility to use low grade/less expensive fuels
  - $\text{SO}_x$ and $\text{NO}_x$ reduction without secondary measures
  - Simple fuel feeding system

- Additional potential advantages in oxyfuel operation
  - High $\text{O}_2$ concentration designs – turbulent bed and heat exchanger arrangements provide good means of equalising temperature levels
  - Flexi-Burn™ – Easier to enable same boiler to be operated with both air and oxyfuel firing
  - No fuel pulverising – no need for primary recyle flow
  - Furnace at overpressure – easier to minimise air ingress

The INTegrated Recycle heat EXchanger (INTREXTM) - an additional advantage in oxyfuel operation in terms of combustion temperature control.
Hamburg OxyCFB study – Summary

Disadvantages/issues:
• Boiler island auxiliary consumption – slightly lower plant efficiency
• Limestone consumption
• Ash flows and disposal issues
• Erosion of reactor walls – although rare in new CFB designs

Uncertainties, risks and development needs:
• So far only small scale OxyCFB test rigs (< 100 kW)
• Further validation in pilot and demo scale necessary (as for PF Oxyfuel)
• Uncertainties related to:
  – Ultra-supercritical steam data (> 600°C) in both air and Oxyfuel operation
  – In-bed SO₂ capture in Oxyfuel operation
  – Combustion control systems
  – Heat transfer in Oxyfuel operation

Vattenfall will continue to follow development of oxyfuel CFB technology closely!
Thank you!

For further information please contact:

Nicklas Simonsson
Vattenfall Research & Development AB
tel.: +46 (0)8 739 5561
nicklas.simonsson@vattenfall.com
Back-up
OxyCFB DH profiles efficiency distribution

Electrical and total efficiencies in the operating profiles

<table>
<thead>
<tr>
<th>Profile</th>
<th>Electrical Efficiency [%]</th>
<th>Total Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile 1</td>
<td>67.9</td>
<td>29.7</td>
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<tr>
<td>Profile 2</td>
<td>66.1</td>
<td>31.7</td>
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<tr>
<td>Profile 3</td>
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<tr>
<td>Profile 4</td>
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<td>35.4</td>
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<tr>
<td>Profile 5</td>
<td>35.6</td>
<td></td>
</tr>
<tr>
<td>Yearly average</td>
<td></td>
<td>33.2</td>
</tr>
</tbody>
</table>

Yearly average: 58.8%
Efficiency summary

- Efficiency penalty condensing operation:
  - 8.5 %-points

- Efficiency penalty district heating operation:
  - 8.2 %-points

- Efficiency penalty lower in district heating operation due to better possibilities for low temperature heat integration
ASU oxygen purity optimisation study

Impact of ASU O2 purity

- CO2 avoidance cost
- CO2 capture cost
- CO2 capture rate

Oxygen purity [%]

CO2 cost [€/ton]

CO2 capture rate [%]